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AN INSTRUMENT FOR THE DETERMINATION

OF RAIN DENSITIES IN FLIGHT

By John R. Bemis and Henry G. Houghton, Jr.
Massachusetts Institute of Technology

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ADVANCE RESTRICTED REPORT

AN INSTRUMENT FOR THE DETERMINATION OF RAIN DENSITIES IN FLIGHT

By John R. Bemis and Henry G. Houghton, Jr.

INTRODUCTION

This project was initiated as a result of some airline experiences of partial or complete engine failure in flight in heavy rain. Preliminary tests on the ground indicated that a concentration of 20 to 50 grams of water per cubic meter of air was required to reproduce the effects on the engine which were observed in flight. The purpose of the work described in this report was to develop an instrument for the determination of rain densities in this range in flight. The major requirements for such an instrument are ease of operation, minimum weight and bulk, rapid response and simplicity of installation. With this in mind, no attempt has been made to study exhaustively all possible means of measuring the rain density; but rather, the principal emphasis has been placed on methods which showed good promise of meeting the foregoing requirements.

The work described in this report falls naturally into two parts. It was first necessary to design and to install proper pumping and spraying equipment in a wind tunnel to simulate flight conditions in heavy rain. This also involved the development of a standard method for the measurement of the rain density produced in the tunnel. The second part of the work comprised the development of the rain density instrument and its calibration. The end result is an instrument which operates on the kinetic energy of the raindrops and in effect measures the ratio of the mass of water to the mass of air.

TEST FACILITIES

The wind tunnel used in these investigations was originally designed for icing research. It is located on the roof of the Guggenheim Aeronautical Laboratory at the Massachusetts Institute of Technology. The general design of the tunnel is shown in figure 1, from which it can be seen that it is an open-end, nonreturn type with a circular cross section. The measuring section is 3 feet in diameter and the fan section is 5 feet in diameter. The over-all length is 32 feet. The fan is a 65-horsepower light airplane propeller cut down to 5 feet and connected directly to a 20-horsepower 3-phase wound rotor induction motor with a maximum speed of 1750 rpm at full load. Variable external rotor resistances make it possible to vary the speed over a considerable range. Maximum velocity in the measuring section is 80 miles per hour. Since the tunnel was not designed for aerodynamic investigations, no special attempt was made to obtain ideal flow in the measuring section, but the velocity profiles in figure 2 show that it is entirely adequate for this work.

WATER-SPRAY SYSTEM

The nozzle array for the icing work is indicated in figure 1. It was entirely inadequate for the rain density work which was estimated to require an output of about 15 to 18 gallons per minute. Although it is not known what rain densities actually occur in the atmosphere, computations and some observational data indicate a maximum value of about 50 grams of water per cubic meter of air. The spray nozzles were designed to produce this density in the measuring section at full tunnel speed. It was planned that slightly higher densities could then be obtained by reducing the speed of the tunnel, and lower densities by reducing the nozzle output. Thirteen spray nozzles (T-30128) manufactured by the Spray Engineering Company were used. These nozzles give a hollow cone spray and thus, even though placed as far upstream as possible, about 20 percent of the output was lost on the walls with the first nozzle array. This was modified to the array shown in figure 3 with a resultant decrease in the loss on the walls and no bad effect on the spatial distribution of the spray in the measuring section. This setup with nozzles placed just behind the honeycomb (as was the original array in fig. 1) seemed to be adequate for the initial tests.

No city water was available on the roof; and consequently the water system used consisted of a bronze gear pump fed from two storage tanks with a total capacity of about 750 gallons. The pump was rated to give an output of 19 gallons per minute at 100-pounds-per-square-inch pressure and 1800 rpm. It is driven by a 2-horsepower 1750 rpm induction motor. Water pressure, indicated on a Bourdon gage, is varied by means of a bypass valve around the pump. The output of the nozzles is proportional to the square root of the pressure, as is shown in figure 4 for a single nozzle.

Due to the convergence of the tunnel at the measuring section, the effect of gravity on the drops, and the wide angle of spray of the nozzles, a considerable portion of the spray was lost on the tunnel walls, as previously pointed out. This water collected as a small stream in the bottom of the tunnel. In order to prevent severe damage to the propeller that would result from the flow of water, a scoop collector was placed in the tunnel as shown by point C in figure 1. A water drain was also installed as shown by point B in figure 1. The motor was protected by a sheet-metal housing with suitable provisions for ventilation.

CALIBRATION

The original plan was to determine the rain density in the tunnel from the total amount of water pumped and the airspeed. However the considerable loss of water on the walls and the recognizable lack of a uniform distribution of the spray across the measuring section made this plan impractical. Another method was therefore resorted to. An open-end tube placed into the tunnel and facing upstream was used as a collector. By maintaining a flow into the tube equal to the tunnel velocity, the possibility of the loss of the smaller drops was eliminated and the water collected by the tube accurately represented the water present in the volume swept out by the tube. As originally constructed, this instrument consisted of a brass tube 12 inches long with an inside diameter of 0.82 inch and a wall thickness of about one thirty-second inch. This tube was pointed directly upstream and was connected to a collector which removed the entrained water and conducted it to a suction pump. Much of the water collected was deposited on the walls of the tube and the connecting pipe. This unit was designed so that all the water would run into the sump below the collector. A small pitot tube was mounted inside the collector tube and a duplicate was mounted in the tunnel air stream. The suction pump was then adjusted so that the pressure difference between the two tubes was as near zero as possible.

The procedure followed was to allow the collector to run for sufficient time to establish equilibrium conditions and to measure the water collected during a known period, usually 5 to 10 minutes. Using the area of the collecting tube, the rate of water collection, and the tunnel airspeed, the rain density was computed readily. The entire collector was arranged so that it could be moved to various positions in the measuring section. The positions of the various stations at which measurements were made are shown in figure 5. The data obtained are given in tables I and II and in figures 6 and 7. Table I and figure 6 show the distribution of water density at various positions in the measuring section at an airspeed of 69 miles per hour and a water pressure of 50 pounds per square inch. Some nonuniformity is apparent but there is a region near the center of the tunnel which is entirely satisfactory for the testing of rain-density instruments. The density is particularly low near the wall because of the deflecting action of the converging section and the loss of water on the walls. The precision of the measurements is believed to be about 5 percent except as noted in table I.

In table II and figure 7 is indicated the effect of water pressure on the rain density at station 1 with an airspeed of 69 miles per hour. From these data it would appear that the density may be varied from about 25 to 40 grams per cubic meter in this way. The effect of variations in the airspeed was not investigated because some difficulty was encountered in maintaining the proper distribution of the spray at lower speeds and because any reductions of speed seemed a step away from the actual operating conditions which were being aimed at. At lower speeds the path of the drops through the measuring section began to depart noticeably from the horizontal and much more of the spray was lost on the walls. It was possible to increase the rain density very little, and a poorer simulation of actual flight conditions resulted. With a closer-fitting more-efficient propeller, tunnel speeds up to 80 miles per hour were obtainable but the proper rain densities put so much water down the tunnel that it was not possible to operate without more clearance in the bottom of the tunnel. For this reason a slightly shorter propeller was used which gave operating speeds of 65 to 69 miles per hour.

MODIFICATIONS OF THE SPRAY NOZZLE ARRAY AND THE CALIBRATION PROCEDURE

The wind-tunnel arrangement with the slightly shorter propeller, although not considered entirely satisfactory, provided reasonable conditions for initial observations of various types of instrument. For final testing and calibration, further modifications were clearly necessary.

Several different types of spray nozzle were investigated in an attempt to obtain a more uniform distribution and a better concentration of the spray at the measuring section to reduce the losses on the walls. Some of these nozzles gave satisfactory results with respect to distribution and concentration of the spray, but failed to give good output over a sufficiently wide pressure range to make possible an adequate variation of rain density.

The original type of nozzle proved best over a wide pressure range, and the spray characteristics were greatly improved by concentrating the group of nozzles at the center of the tunnel rather than attempting to distribute them over the 5-foot section. The best array finally proved to be a group of 10 type T-3012S nozzles arranged in a ring 7 inches in diameter and placed at the center of the 5-foot section just inside the honeycomb, as before. This gave a good distribution covering the proper range of densities over an area in the center of the tunnel about 20 inches in diameter. In the pressure range from 20 to 100 pounds per square inch, densities could be produced in the measuring section from 20 to 55 grams per cubic meter which covers the entire range considered necessary.

For calibration it also proved advisable to develop an improved method of checking the rain density at various points within the measuring section. Slight clogging of one nozzle often produced marked variation of density and so for final calibration frequent checks were deemed necessary. In testing the NACA collecting scoop (see later discussion and fig. 8) it was found that no significant change in the rate of collection was evident when measurements were made with this or the test collector tube, either with or without a flow into the orifice being maintained by means of the pump. Consequently a revision of the original collecting tube was made, as shown in figure 9. The revised water collector has the same orifice diameter (0.82 in.) and connects by means of a rubber tube with a bottle to even out the rate of flow. The overflow from the bottle goes to a calibrated tube for measuring the volume of water collected. The testing procedure was to allow the system to reach equilibrium and then to measure the time required to collect 50 cubic centimeters of water. Results, checked within 1 or 2 percent, and data could be obtained with reasonable speed so that frequent checks were possible.

INSTRUMENT DEVELOPMENT

In designing an instrument for a specialized purpose, such as measuring rain density from an airplane in flight, consideration has been given to the limitations which such use would impose on it. This investigation has therefore been limited to methods which showed the best possibilities for adaptation to flight conditions. In addition to the obvious limitations of size, weight, ease of installation, operation, and so forth, it has been deemed advisable to incorporate other features in the rain density instrument. Since the densities involved may be expected to show quite rapid changes and fluctuations, it was believed that the device should be direct reading with a fairly rapid response to change. Because most methods of measuring rain density are dependent upon the speed of the airplane, it was also felt that the device should be independent of airspeed so that it reads the rain density directly without the necessity of simultaneously recording airspeed.

METHODS OF MEASURING RAIN DENSITY

Numerous different methods of measuring the amount of water encountered in air have been suggested. The most obvious and direct of these is to catch the water and measure it. A slightly less direct method is to measure the force of impact or the kinetic energy of the drops. Another method suggested is to measure the transmission of light through the rain. This method was not considered in the present study because light transmission is a function of the size of the drops. Another possibility for measuring the amount of water is to allow the air to pass between the plates of a condenser and measure the change in capacity due to the entrained water. This method was discarded because it involved too many doubtful quantities and probably too much electronic experimentation for a preliminary instrument of this type. Work has been confined chiefly to systems based on the first two methods mentioned above.

RAIN COLLECTORS

The NACA has designed and utilized a rain-collector scoop (see fig. 8) which, except for icing problems, was satisfactory. The NACA collector scoop has been tested in the M.I.T. wind tunnel and the results compared with data obtained on the collector tube that was developed in this research program. At a tunnel speed of 69 miles per hour and at a water density of 23.1 grams per cubic meter measured by the collector tube, the NACA collector scoop indicated a density of 23.4 grams per cubic meter with the blower attached and 22.3 grams per cubic meter when connected directly to a closed bottle. These readings are all within the limit of accuracy of the measuring equipment used and indicate that both devices are about equally effective collectors.

The chief problem in designing a good instrument of the collector type is to devise a reliable method of measuring the rate of accumulation or rate of flow of the water. Several different methods were investigated, utilizing small orifices for measuring the rate of flow. The small orifices proved subject to plugging difficulties and were found to be poorly adapted to the necessary range of about 10 to 35 grams per cubic meter. Dumping devices do not appear to be adapted for operation in an airplane. All such methods give a slow response to changes in rate of flow and thus would tend in operation to obscure such changes. In addition, a satisfactory method of correcting for the effect of airspeed in order to record density directly could not be readily devised.

These difficulties made it advisable to utilize a method of measuring the impact of the drops which showed better promise of overcoming these problems.

IMPACT INSTRUMENTS

After considerable experimentation with methods of constructing a sensitive diaphragm and waterproof pitot heads, a simple method was devised for constructing the impact diaphragm so that the dynamic pressure of the air was eliminated. With these principles as a basis for construction, a rain-density measuring instrument has been developed.

A diaphragm or plate such as AB in figure 10 mounted at the orifice of a closed system so that it is free to move in and out, as indicated by the arrows C and D, will tend to come to equilibrium in some position close to the mouth of the orifice when placed in an air stream as indicated. At this point the pressures on the back and front of the plate are equal. If it is moved back in the direction D, the pressure is slightly lower on the front than on the back of the plate as a result of the flow over the orifice, and it tends to return. If it is moved forward in the direction C, the pressure is higher on the front than on the back so that it moves back to the equilibrium position. Thus when exposed to the air stream the diaphragm remains at a fixed position. When rain is encountered the diaphragm is forced back from the equilibrium position by the impact of the drops. The force of the drops is large with respect to the force tending to move the diaphragm forward, so that an additional restoring force is required to prevent it from being forced back to the limit of its movement. In order to eliminate the effect of airspeed, this restoring force must vary with the square of the airspeed. Another diaphragm of a similar nature will supply such a force, for in moving forward from the equilibrium position, AB is exposed to the dynamic pressure of the air. The pressure has been found to increase at a nearly constant rate from zero at the equilibrium point until it approaches the dynamic pressure at a point about 0.1 inch from the orifice (if the orifice is threefourths in. in diam.). Thus a restoring force may be obtained which increases with displacement and which varies closely with the square of the airspeed, as does the dynamic pressure. If the instrument is equipped with a means of reading the displacement, it may be calibrated directly in terms of rain density.

If the two diaphragms of areas A_1 and A_2 are balanced on opposite arms pivoted at the point F, as shown in figure 11, it will be possible to set up an equation for the balance of the forces acting on the two arms. If diaphragm A_1 is assumed to recede under the impact of the waterdrops and if diaphragm A_2 moves forward and provides the restoring force, the ratio of the lengths of the two lever arms for the maximum rain density which the instrument is expected to measure can be determined. The dynamic pressure is proportional to the product of the density and the square of the velocity. Since the density of the rain at a maximum possible value of 60 grams per cubic meter will be about 5 percent of the air density at sea level, the dynamic or impact pressure of the rain can be expressed as 5 percent of the dynamic pressure of the air. Then, if the restoring diaphragm is considered to be exposed to the full dynamic pressure of the air at its maximum extension, the relationship between the lengths of each arm and the areas of each diaphragm can be set up. Following the symbols used in figure 11, with the two areas equal to A_1 and A_2 and letting D equal the dynamic pressure of the air, the following simple relationship results:

$$0.05\ D\ A_1\ a_1 = 0.05\ D\ A_2\ a_2 + D\ A_2\ a_2$$

or

$$0.05 A_1 a_1 = 1.05 A_2 a_2$$

$$A_1 a_1 = 21\ A_2 a_2$$

With this as a basis for design, a test instrument, shown in figure 12, was built for preliminary trial. Practical considerations limited the selection of the values for two of the variables. First, neither of the arms should be so short that the angular movement of the diaphragms would be large in proportion to the forward and backward or tangential movement. A length of 2 inches was felt to be a safe minimum and so a_2 was fixed at this value. Secondly, it was desirable to have A_1 sufficiently large so that it would receive a representative sample of the drops and would not be responding to the individual drop impacts. A diameter of 1.5 inches seemed a safe value for A_1, and A_2 was more or less arbitrarily set at 0.75 inch. This gave a_1 a length of 10 inches and the whole instrument an over-all length of 13 inches. Indication of density was made by reading the position of the arm. Its case is so constructed that air flow between the two orifices due to any pressure differences will be negligible. If any flow is allowed to pass through the orifices, it affects the action of the diaphragm. It was found that a passage one-eighth inch in diameter between the two orifices permitted sufficient flow to affect the operation.

Testing revealed that the calculated proportions appeared to cover the proper range of densities. This model was built with as light an arm and diaphragms as possible, which were mounted on jewel bearings with the result that it responded far too readily to all the fluctuations in impact on the diaphragms. More damping was obviously necessary, particularly for the higher densities. When close to the zero position and on it, very good stability was shown.

Considerable time was spent in developing an adequate position-indicating device, and after trying several different methods, a small portable electronic device, shown with the second model in figure 13, proved the readiest solution. The circuit shown in figure 14 consists of a small oscillator of the negative resistance type, and a power amplifier stage which feeds through a transformer into an intermediate frequency coil. The output from this coil is picked up by another similar coil and is rectified in the final stage by using the 1 H5GT tube as a diode. An aluminum shield mounted on the moving arm of the instrument comes between the two coils as it moves back and varies the current picked up by the second coil as a result of the eddy current induced in the plate. A frequency of about 20,000 cycles at the top of the audio range is used and readings are given on a small (0.50) microammeter. The tubes are all small battery type and power is supplied by self-contained batteries.

The model shown in figures 13 and 15 was made up as an instrument which would be suitable for preliminary flight tests. The dimensions chosen were made the same as those which had been indicated as satisfactory on the first tests. Two small ball bearings were substituted for the jewel bearings in order to permit making the arms and diaphragms heavier to provide some inertia damping. The case was of welded-sheet aluminum and a removable plate was provided to give access to the bearings. The coils of the indicating instrument were mounted as shown just back of the impact arm.

This instrument has been tested in water densities from 20 grams per cubic meter up to 55 grams per cubic meter at 65 miles per hour. In order to check its zero position stability, the device has been operated at speeds up to 110 miles per hour in the 5- by $7\frac{1}{2}$-foot wind tunnel at M.I.T. These tests carry the investigation about as far as is possible with the existing facilities. They show that three simple modifications probably should be made. More mass should be added to the two arms or some other means of providing additional damping at the higher densities should be devised. The area of the "impact arm" should be reduced to a circle 1-1/8 inches in diameter. More careful measurements have shown that the sensitivity is too great and at the top of the range (45 to 50 grams/m^3) the arm was reaching the end of its 1/2-inch movement. This is presumably due to the fact that full dynamic pressure is not developed over the entire area of the restoring diaphragm and also due to the somewhat greater instability at these higher densities. The addition of more mass would correct the latter difficulty but it is felt that a reduction in the size of the diaphragm would improve the operation by reducing the degree of movement. In the test instrument the area of the impact diaphragm has been reduced with an improvement in performance. The size of the orifice has not been reduced accordingly, however, so that the full advantage of the reduced area is not obtained.

The third detail requiring further attention is the position-indicating instrument. At the time this was constructed the only meter available was a small Triplett instrument with a 3-inch dial; a larger slightly more sensitive meter would improve accuracy. The existing circuit undoubtedly can be improved and can be made more compact. It was designed to result in a good working instrument and little time has been devoted to refining it. The instrument appears to possess good stability and the oscillator circuit has excellent sinusoidal wave form. A period of about two minutes should be provided for allowing the instrument to warm up and reach equilibrium, as the readings do not become stabilized at once.

Other alterations will be necessary before the instrument can be considered a finished product. Because of the construction of the existing model, access to the working parts and assembly is a fairly intricate process. A method utilizing castings, preferably of aluminum, is suggested. If made in top and bottom halves, adjustment and inspection of the working parts would be simplified; and by providing for slight adjustments in the pivot point, final balancing would be facilitated.

The problem of protecting the instrument against icing conditions which might frequently interfere with obtaining rain-density data has not been considered. This could presumably be taken care of by providing an adequate means of applying heat.

As indicated above, the restoring force provided by the dynamic pressure of the air, though correcting for airspeed, will also be dependent upon the density of the air. As the air density decreases, the restoring force will correspondingly decrease. It is not expected, however, that over the range of altitudes at which observations will normally be made that this will offer a serious objection. Data on altitude would normally be taken, rapid and large changes would usually not be encountered, and the correction would be a very simple one to apply.

Data on calibration of the preliminary model are given in table III and in figure 16. These data include deflection of the impact diaphragm from its maximum forward position in inches with the corresponding water pressures on the spray head and rain density.

The plot of these data in figure 16 indicates a marked change in slope at about 30 grams per cubic meter. It is not considered probable that this is due either to an accumulation of water in the orifices or to a change in the character of the air flow. The discrete impacts of individual drops cause an oscillation or buffeting of the diaphragm at all rain densities. At densities above 30 grams per cubic meter the arm reaches the limit of its travel in its backward oscillations, and the mean reading as indicated on the meter is correspondingly too low. This difficulty could be eliminated by providing more travel or by reducing the size of the diaphragm as already suggested. More effective damping would also tend to reduce the amplitude of the oscillations. It is also probable that an increased airspeed with the corresponding increase in the number of drop impacts per unit of time would further reduce this effect.

CONCLUDING REMARKS AND RECOMMENDATIONS

It is regretted that delays in the preparation of the test instrument prevent inclusion in this report of any data on flight tests. Plans have been made, however, to conduct tests of the rain-density instrument on a transport airplane of one of the commercial airlines, data to be taken during regularly scheduled flights.

The problem of adapting this or any other instrument to operation on an airplane can be accomplished only under actual flight conditions. The problems encountered in developing the testing facilities clearly show the limitations of such equipment. The question of applicability of calibrations made in a wind tunnel to flight conditions also must be answered by fairly extensive flight tests and it appears that readings should be obtained in flight from both this and a collector-type instrument to obtain the final calibration. Considerable study will be required to determine the proper location on an airplane for installing such an instrument. The present investigation has provided a basis for the design of an instrument which, in the final model, is expected to prove an adaptable and convenient means of obtaining extensive data on the now unknown quantity of rain density.

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Cambridge, Mass.

TABLE I

DENSITIES AT VARIOUS POSITIONS IN THE TUNNEL MEASURED AT 69 MILES PER HOUR AND A WATER PRESSURE OF 50 POUNDS PER SQUARE INCH

Station	Rain density (grams/m^3)	Number of runs	
1	30.9	4	
2	30.9	3	
3	13.7	3	
4	5.0	1	
5	40.4	3	
6	37.8	3	
7	25.8	3	
*8	30.5	3	runs check within 6 percent
9	28.0	3	
10	29.5	3	
11	29.8	3	
*12	30.3	3	runs check within 7 percent
13	41.0	3	
14	34.8	3	
15	36.0	3	
*16	24.0	3	runs check within 9 percent
17	23.2	3	
18	20.7	3	
19	24.5	3	
20	24.3	3	
21	30.5	3	

TABLE II

RATES OF COLLECTION AND RAIN DENSITIES FOR VARIOUS WATER PRESSURES AT POSITION 1 AT 69 MILES PER HOUR

Water pressure (lb/sq in.)	Rate of collection (cc/min)	Rain density (grams/m^3)	Number of runs
20	17.8	25.8	3
30	18.3	26.5	4
40	19.5	28.2	5
50	21.3	30.8	4
70	24.6	35.6	5
80	25.6	37.2	3
90	26.1	37.8	3
100	28.2	40.9	9

TABLE III

Dial reading	Diaphragm deflection (in.)	Rain density (grams/m^3)	Pressure on spray nozzles (lb/sq in.)
96	0	0	0
85	.160	20	25
58	.280	28	35
35	.356	35	45
25	.386	45	55
15	.414	50	70

Note: Due to the turbulent water distribution in the tunnel, the irregular impact pressure of the water drops, and insufficient damping of the instrument, the accuracy of readings, especially at the higher densities, is plus or minus 5 percent. The rain density values for the various water pressures on the pump have not been made to exceed an accuracy of 5 percent.

It is expected that under actual flight conditions at considerably higher speeds the stability and accuracy would be much improved.

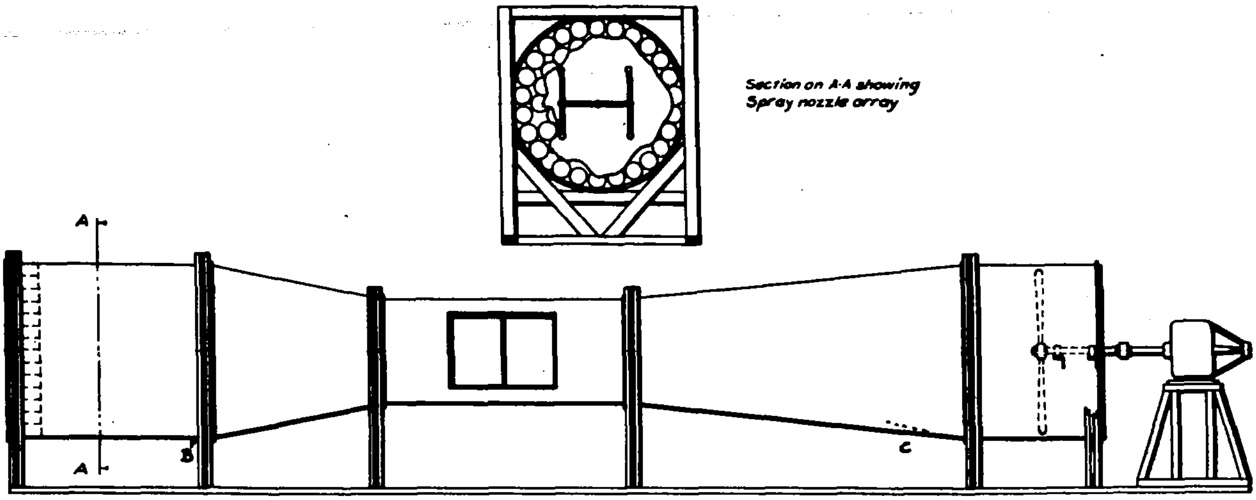

Figure 1.- Icing tunnel.

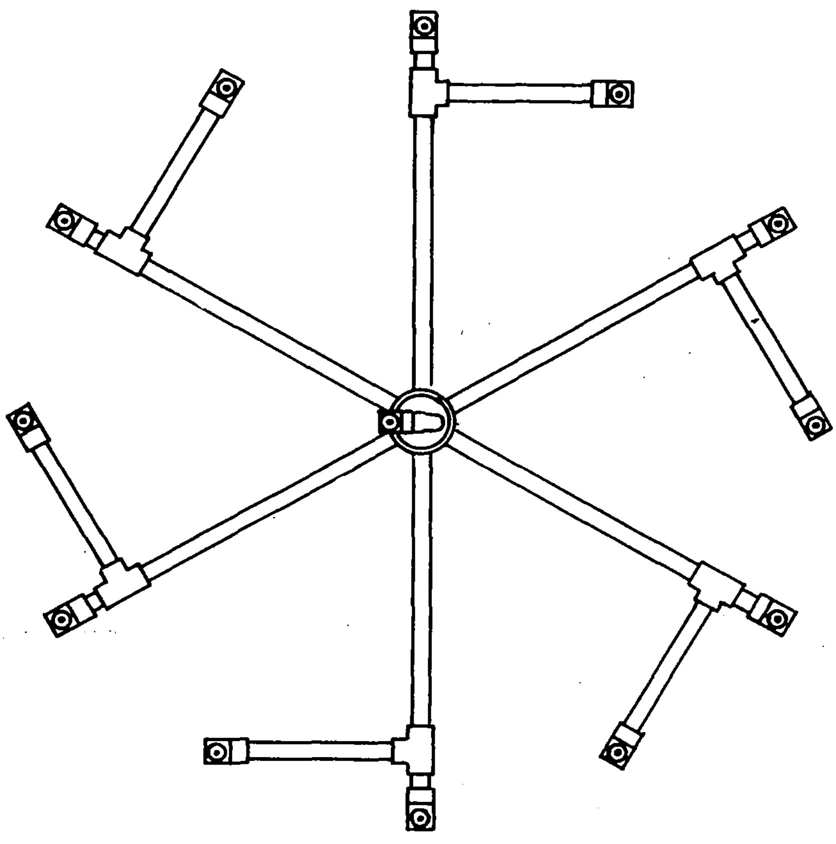

Figure 3.- Nozzle array.

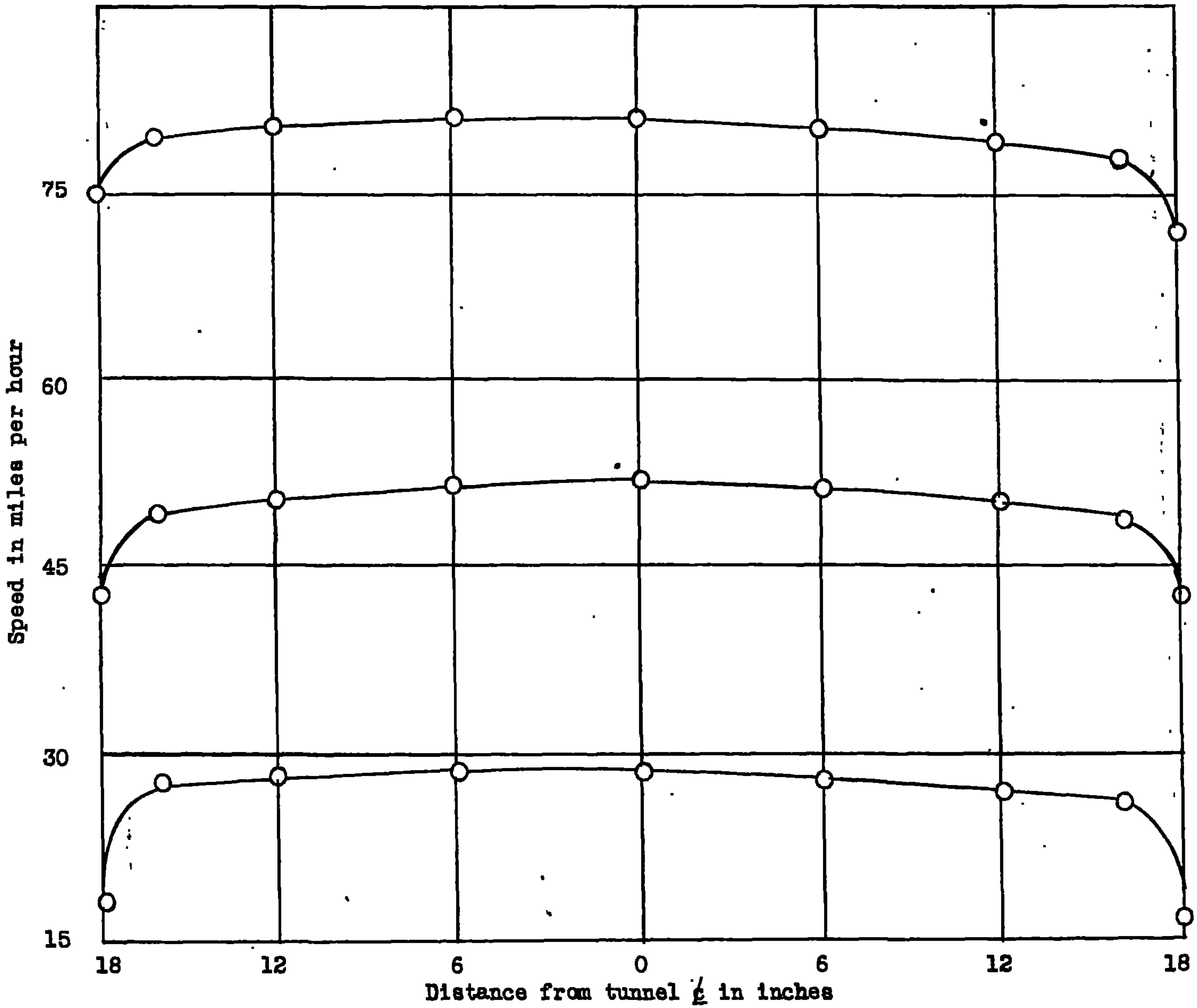

Figure 2.- Tunnel velocity profiles.

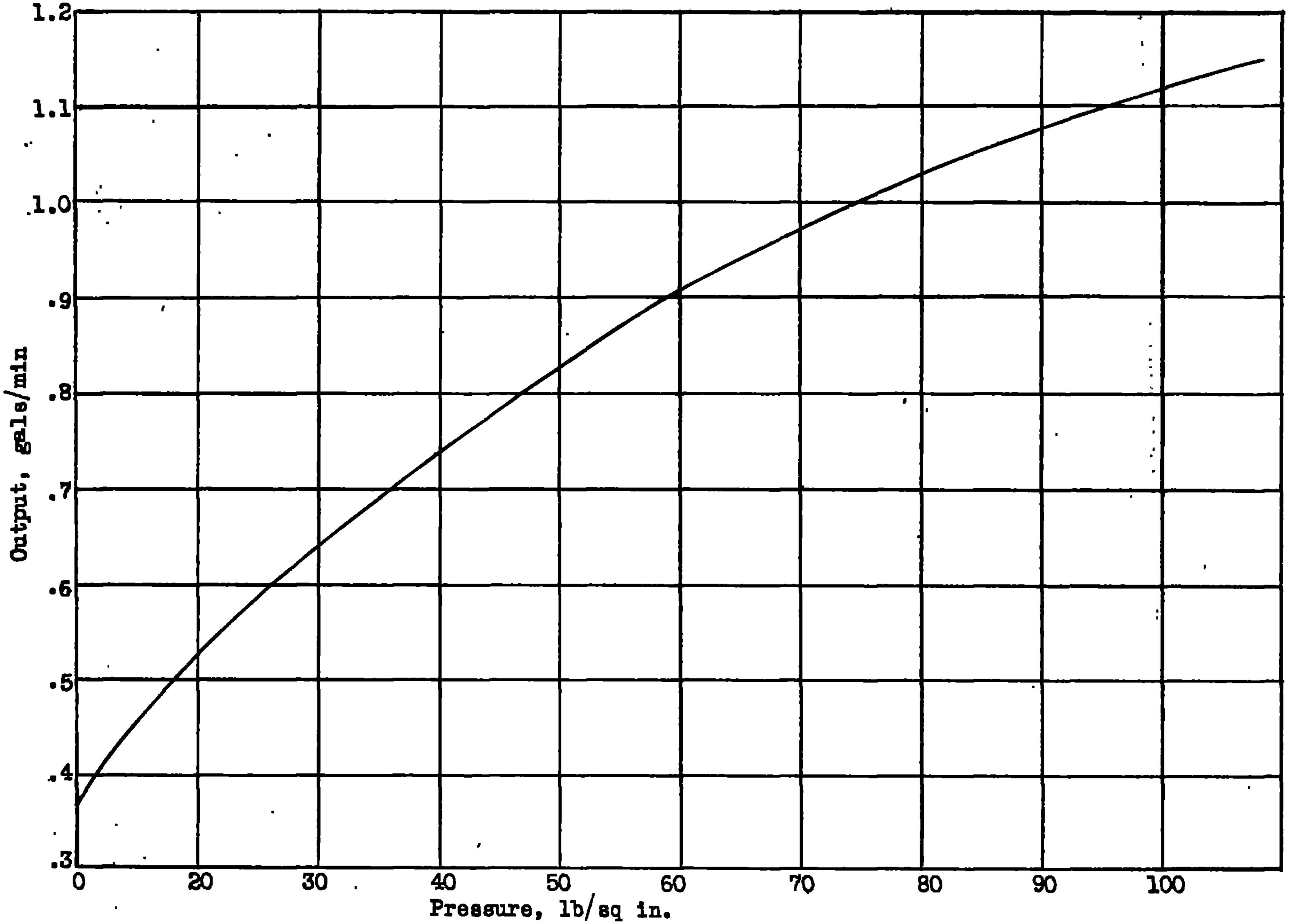

Figure 4.- Water nozzle output.

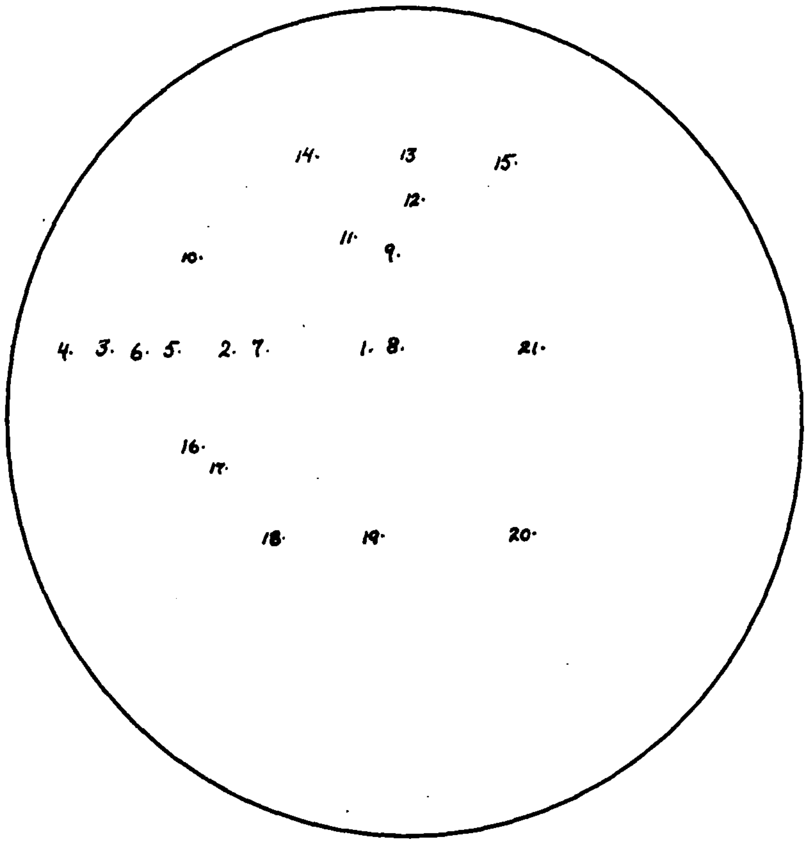

Figure 5.- Location of stations facing down tunnel for measuring rain density.

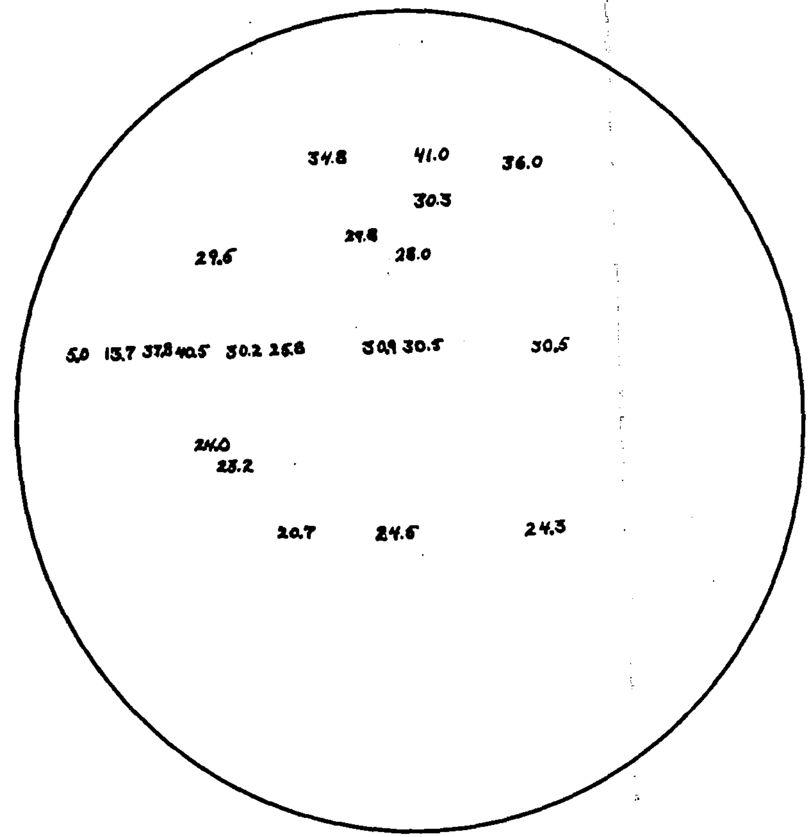

Figure 6.- Water density in grams per cubic meter measured at pressure of 50 lb/sq in. and 69 mph.

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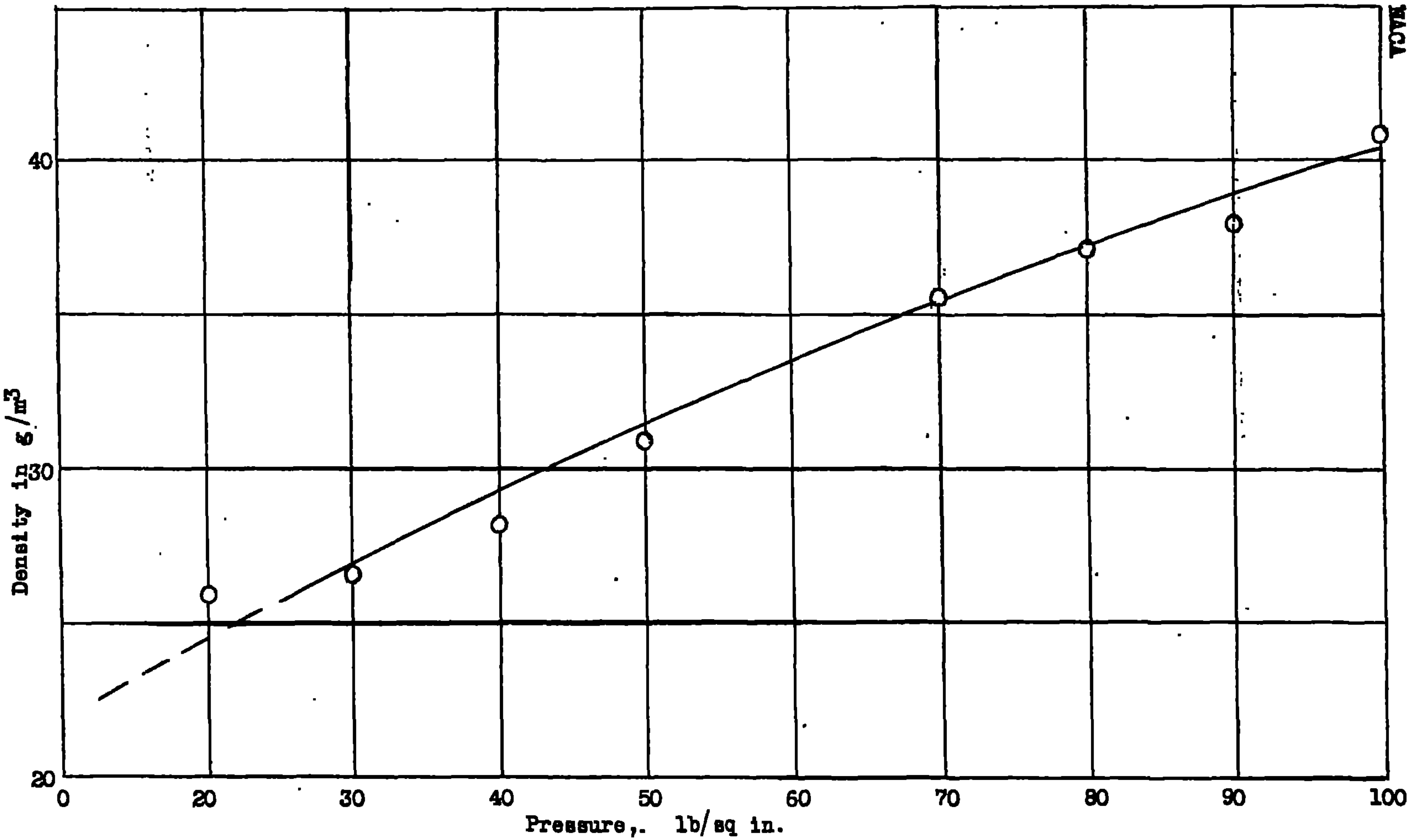

Figure 7.- Effect of water pressure on rain density at station number 1.

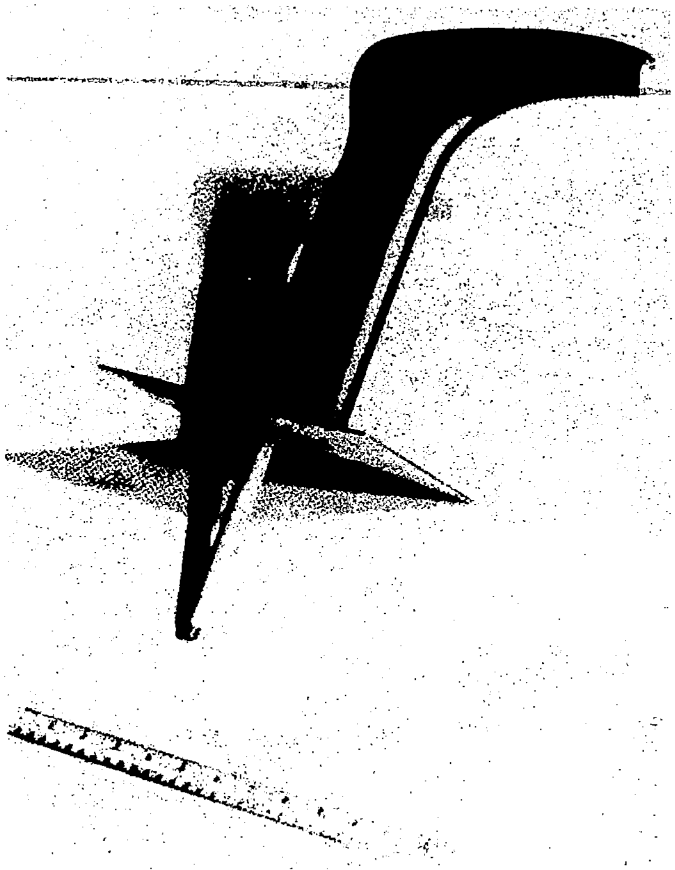

Figure 8.- NACA collecting scoop.

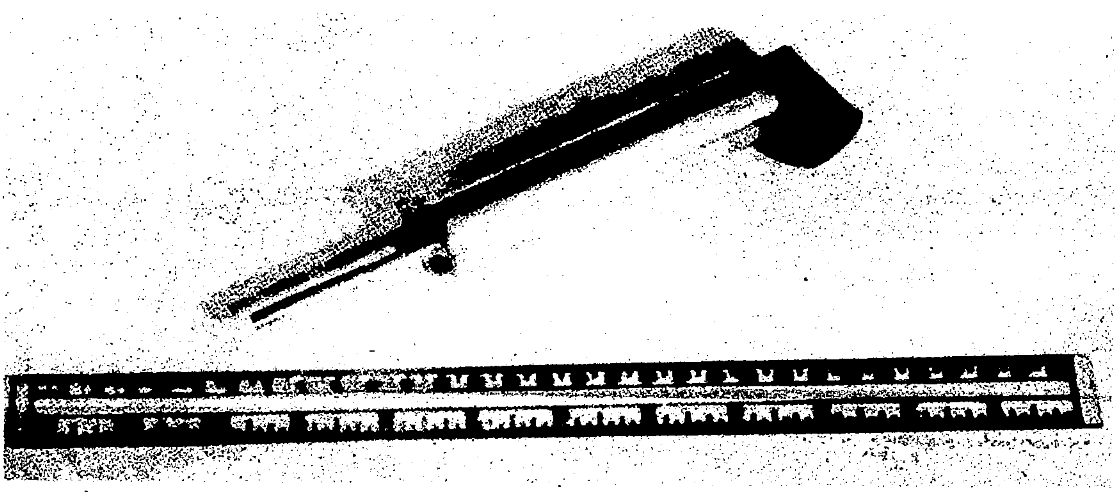

Figure 9.- Water collecting tube.

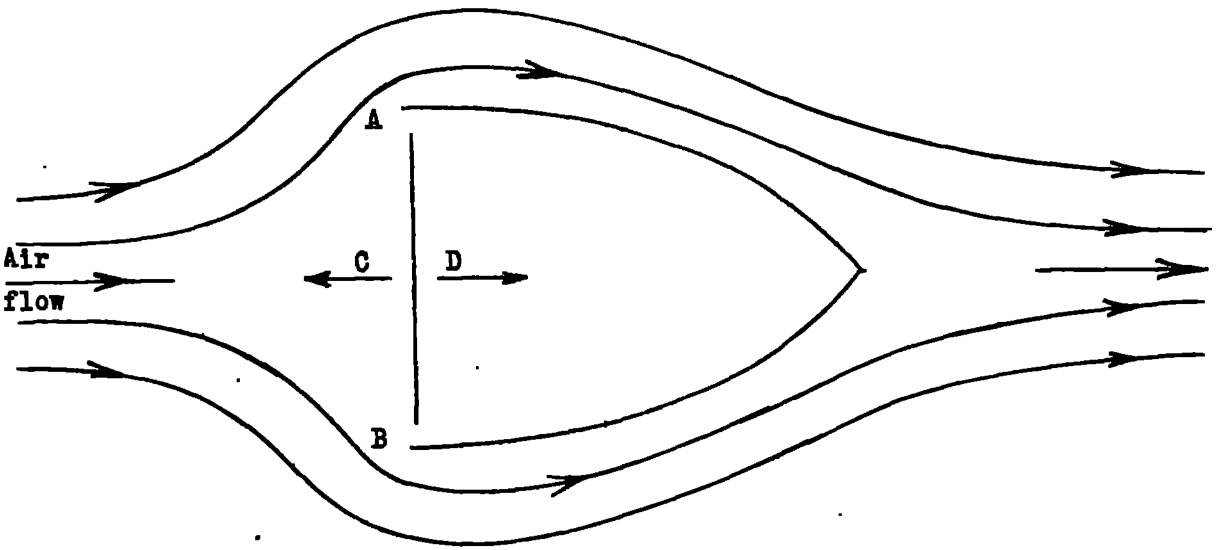

Figure 10.- Action of impact diaphragm in measuring rain density.

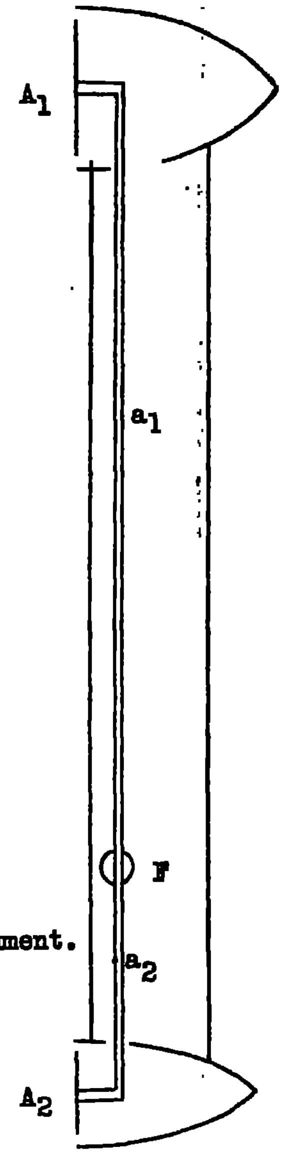

Figure 11.- Sketch of rain density instrument.

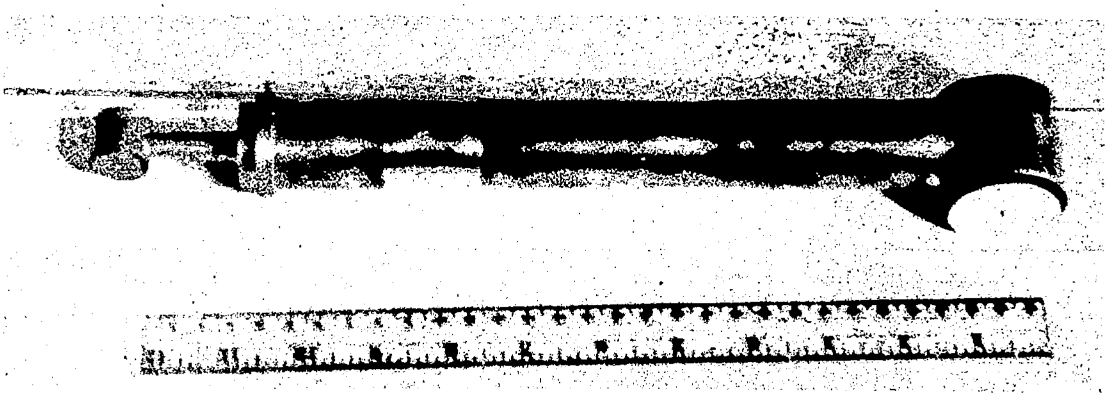

Figure 12.- Tunnel test model of rain density instrument.

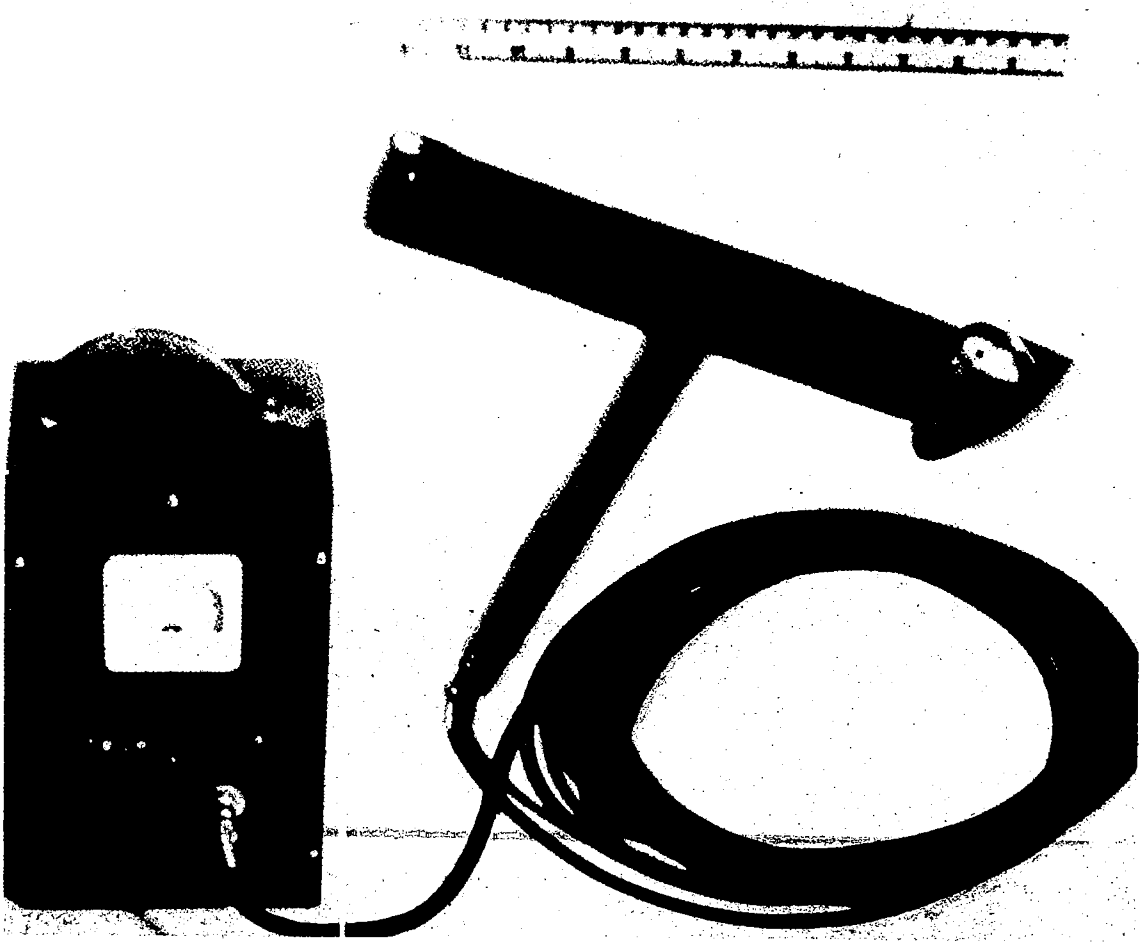

Figure 13.- Preliminary model of rain density instrument for flight tests.

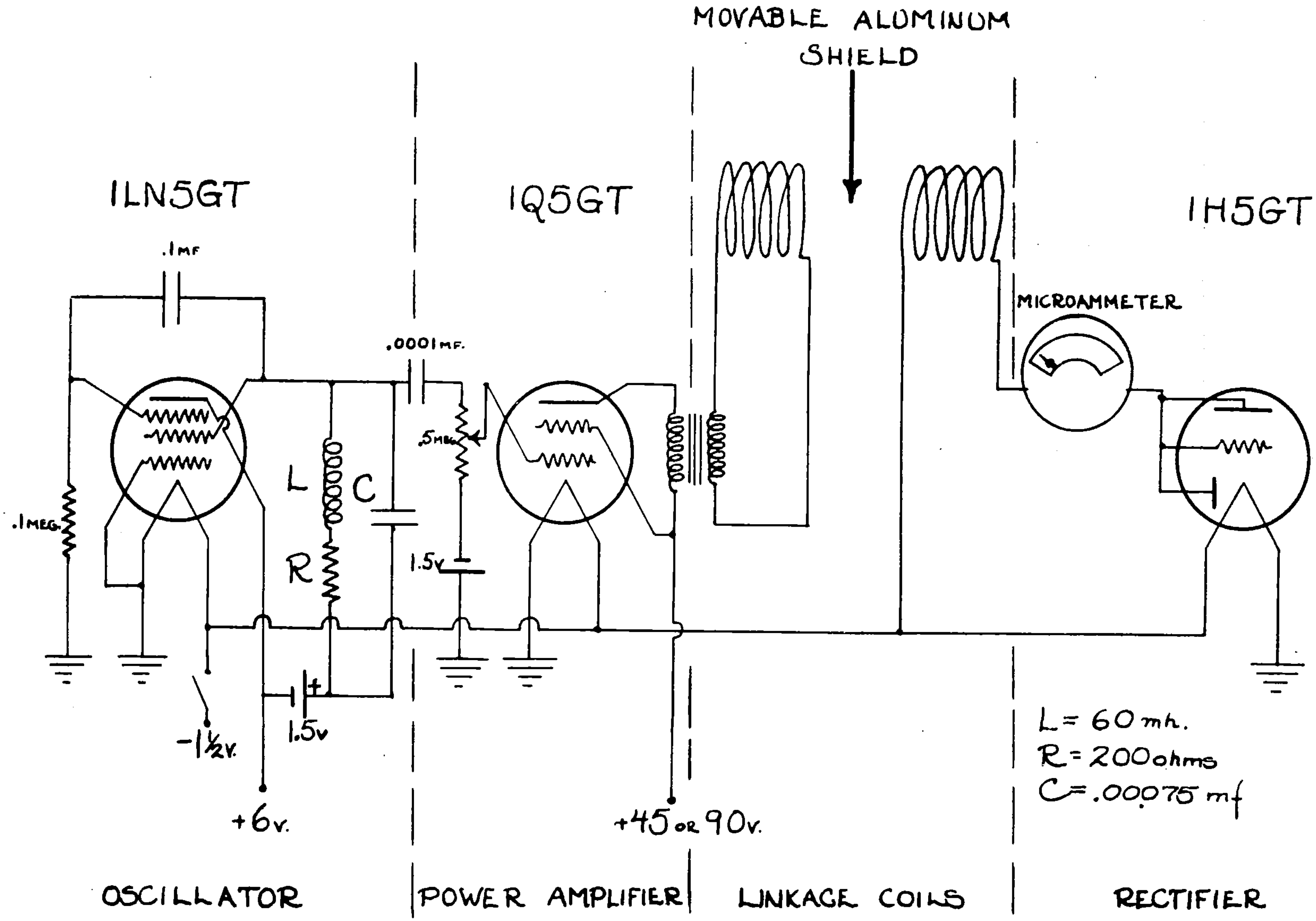

Figure 14.- Position indicator circuit.

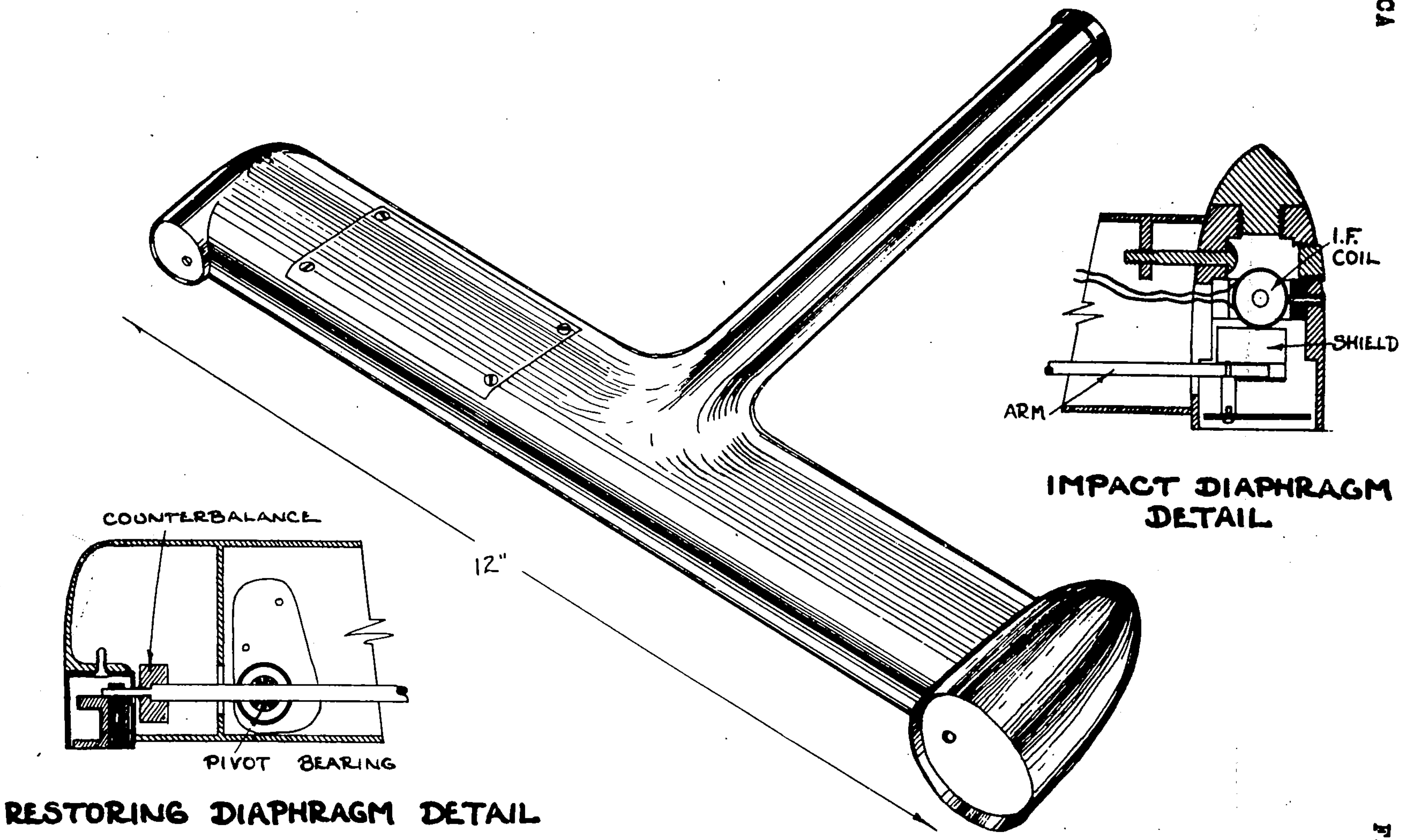

Figure 15.- Preliminary model of rain density instrument for flight tests.

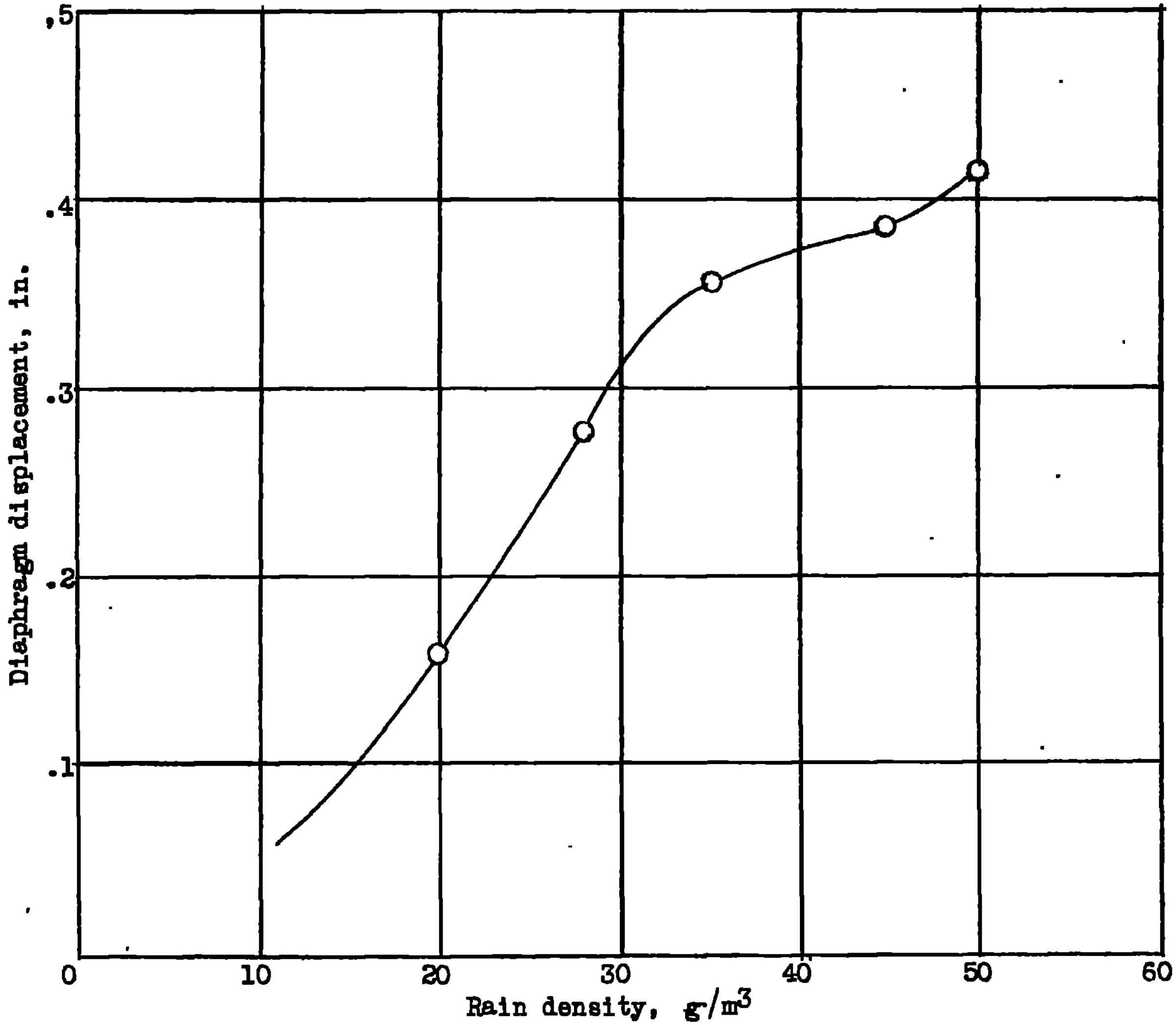

Figure 16.- Calibration of preliminary model of rain density instrument.

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